

AN ALTERNATIVE INTERPRETATION OF THE TIMING NOISE IN ACCRETING MILLISECOND PULSARS

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ABSTRACT

The measurement of the spin frequency in accreting millisecond X-ray pulsars (AMXPs) is strongly affected by the presence of an unmodeled component in the pulse arrival times called ‘timing noise’. We show that it is possible to attribute much of this timing noise to a pulse phase offset that varies in correlation with X-ray flux, such that noise in flux translates into timing noise. This could explain many of the pulse frequency variations previously interpreted in terms of true spin up or spin down, and would bias measured spin frequencies. Spin frequencies improved under this hypothesis are reported for six AMXPs. The effect would most easily be accounted for by an accretion rate dependent hot spot location.

Subject headings: stars: neutron — X-rays: stars

1. INTRODUCTION

Precise orbits and spin parameters have now been reported in 9 accreting millisecond X-ray pulsars (AMXPs; see Wijnands 2004; Poutanen 2006; di Salvo et al. 2007 for reviews, Patruno et al. 2009 for the AMXP most recently found). Yet, controversy still surrounds the interpretation of the observed pulse time-of-arrival (TOA) records. The reason for this is the presence of a red “timing noise” component in the TOA residuals. While on the time scales of hours relevant to determining the orbit this noise has only a moderate effect, its amplitude is large on the timescales of weeks to months required to measure the pulse frequency ν and its time derivative $\dot{\nu}$. The origin of the timing noise is unknown, there is no satisfactory model for it, and no agreement on how to deal with it when measuring ν and $\dot{\nu}$. Some authors fit a constant ν (Hartman et al. 2008, H08 from now on), while others fit a constant $\dot{\nu}$ or more complex models, interpreted as due to accretion torques (Falanga et al. 2005; Burderi et al. 2006; Papitto et al. 2007; Chou et al. 2008; Riggio et al. 2008). Both methods leave unmodeled timing noise in the residuals, and in determining orbital and spin parameters arbitrary rejection is performed of data segments, or of pulse profile harmonics, showing ‘too much’ noise (see Patruno et al. 2009b).

In two AMXPs it was already noted that on short (<10 d) timescales X-ray flux and TOA residuals correlate (J1814, Papitto et al. 2007) or anticorrelate (J1807, Riggio et al. 2008), and on the timescales of weeks similar to the duration of an AMXP outburst these correlations were found to be stronger for a constant ν model than for constant $\dot{\nu}$ (Watts et al. 2008, Patruno et al. 2009b).

Here we show that such correlations are common in AMXPs and can be interpreted in the sense that a given flux level induces a given, constant, TOA offset, so that trends in flux bias the measured ν and $\dot{\nu}$ values. Our findings then suggest that the timing noise is not dominated by accretion torques but instead by accretion rate dependent variations in hot spot location on the neutron star surface.

2. OBSERVATIONS AND DATA REDUCTION

We use all *RXTE* PCA public data for 6 AMXPs (Table 1). We did not analyze HETE J1900.4–2455 and SAX J1748.9–2021 as their weak and intermittent pulsations require special analysis, nor SWIFT J1756.9–2508 and Aql X-1, whose pulse episodes were too brief to be useful.

We refer to Jahoda et al. (2006) for PCA characteristics and *RXTE* absolute timing. We used all available Event and GoodXenon data, rebinned to 1/8192 s and in the 2.5–16 keV band that maximizes S/N. We folded 512-s data chunks, keeping only those with S/N > 3–3.3 σ , giving <1 false pulse detection per source. We detect both a fundamental (ν) and a first overtone (2ν) in our pulse profiles of J1808, J1807, and J1814 and only a fundamental in J1751, J00291, J0929. The former three sources show strong pulse shape variability, so that the fiducial point defining the pulse TOA becomes ill defined (cf. Patruno et al. 2009b). Therefore, we measured the TOAs of fundamental and overtone separately, and then separately fitted them with a Keplerian orbit plus a linear and possibly a parabolic term representing ν and $\dot{\nu}$. The first three sources also have strong timing noise and without modeling this noise both models give reduced $\chi^2 \gg 1$, the latter three have weaker timing noise and reduced χ^2 closer to 1, but both models remain statistically unsatisfactory.

3. PHASE-FLUX CORRELATIONS

Figure 1a (bullets) shows the TOA residuals Δt from a standard fit of a constant ν model, expressed as a phase residual in units of pulse cycles: $\Delta\phi \equiv \nu\Delta t$. The phases show structures that are clearly anti-correlated with short term flux variations (top trace; the concavity at day 2–10, the bump around day 10, the slower decay after day 12). However, there is no correlation with the long term flux decay. Indeed, plotting the phases against flux (Fig. 1b) no correlation is seen.

The reference (ephemeris) pulse frequency ν selected by a standard χ^2 fit is the one that distributes the residuals evenly among positive and negative values; this choice is arbitrary and other choices, introducing a net slope in the plot of residuals vs. time, are equally valid (cf. Patruno et al. 2009b). With this in mind we now investi-

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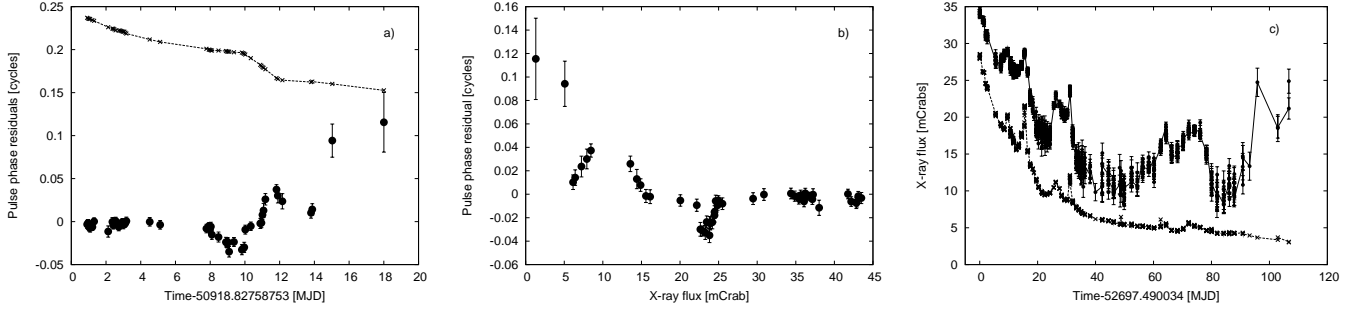


FIG. 1.— **a.** Phase residuals ($\Delta t \times \nu$) from a standard fit of a constant frequency model to the fundamental frequency TOAs in the 1998 outburst of J1808 (*bullets*) and simultaneous 2.5–16 keV light curve (*crosses*) in arbitrary units. Short term correlations are clearly present, but the long term trend in flux is not seen in phase. **b.** Phase vs. flux for the same data. **c.** X-ray light curve and phase residuals of J1807. The phase residuals are shown upside down and in arbitrary units to better visualize the correlation of the short term phase fluctuations with the X-ray flux.

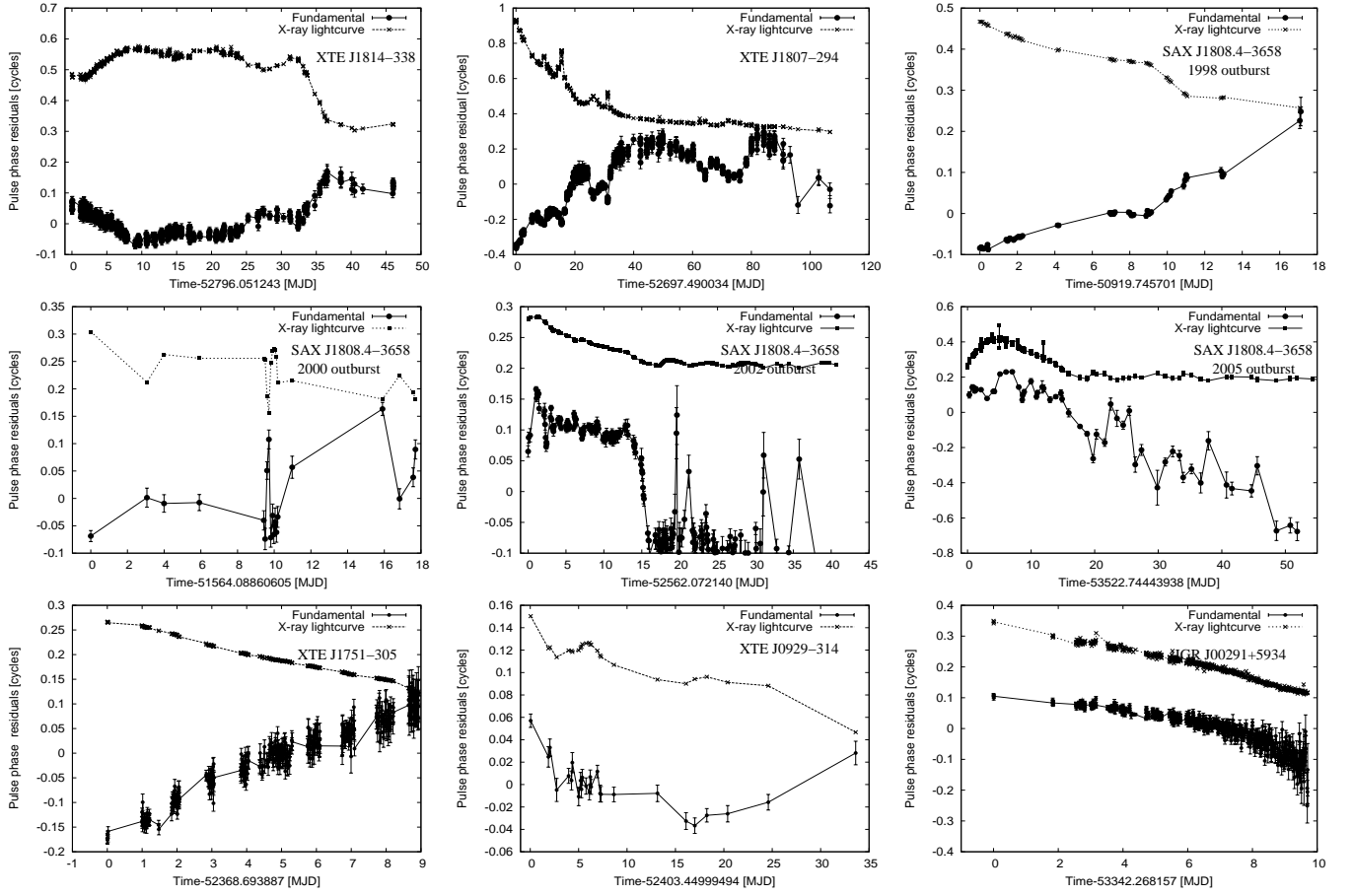


FIG. 2.— Phase residuals of the fundamental frequency and 2.5–16 keV light curves; as Fig. 1a, but with ν that optimizes the phase-flux correlations, see text. Phase-flux correlations can be seen on all timescales.

gate the hypothesis that not only the short-term variations in flux correlate with phase, but also the long term trend in flux correlates with a similar trend in phase over the entire outburst. If true, the best fit pulse frequency is not exactly the spin frequency, but contains a bias that can in principle be removed.

Figure 2 provides similar plots as Fig. 1a for each outburst, but now choosing ν such as to maximize the phase-flux correlation by minimizing the χ^2 of a linear fit to phase vs. flux (Fig. 3). The difference with the standard technique can be seen by comparing Fig. 1a with the top

right panel of Fig. 2. Carefully scrutinizing Figs. 2 and 3, it is clear that short term correlations and anticorrelations such as in Fig. 1a are ubiquitous in our sample, and that with few exceptions (discussed below) with a proper choice of ν (Table 1) these can be matched with a correlation on long timescales. In J1814, the slope of the short term correlation (measured by first subtracting best fit parabolae from flux and phase records) is -16.3 ± 0.5 cycle/mCrab, and that of the long term one -18.9 ± 0.3 cycle/mCrab. So, it looks like it is *phase* that correlates to flux here, not its second derivative $\dot{\nu}$ as in

standard accretion torque models. If we remove this X-ray flux effect from the TOAs of J1814 and then fit a $\dot{\nu}$ model, $\dot{\nu}$ is a factor 15 lower than using the standard method.

The phase-flux correlation we find is positive for some sources and negative for others, and in different outbursts of J1808 both signs occur, but always has the same sign on both long and short time scales. The full phase range implied by the best correlation to the flux decay is always less than one cycle. In J1814 and in the '98 outburst of J1808 the correlation is the same for fundamental and overtone, while in J1807 for the overtone it has a slope ≈ 0.25 that of the fundamental. In the '00, '02 and '05 outbursts of J1808, the phase of the fundamental correlates with flux whereas the 1st overtone exhibits a weak anti-correlation. However, since the 1st overtone has a low S/N and short term fluctuations are difficult to detect, we decided to exclude the 1st overtone from our analysis.

In addition, during the J1808 *re-flaring state* (Wijnands 2004) at the end of the '02 and '05 outbursts (but not the – sparsely sampled – '00 one) the correlations break down: other modes of accretion from the disk might play a role here (see Patruno 2008). We excluded these re-flaring states when reporting ν in Table 1. In Fig. 3 we plot only the points included in the fit; the lines correspond to the frequencies reported in Table 1. In J1807, J1808 and J0929 the pulse phases deviate from the linear correlation below some flux threshold.

The χ^2 values in Table 1 are still unsatisfactory, however, they are a statistically highly significant factor 2–5 smaller in J1807, J1814 and in the 1998 outburst of J1808, and similar in the other six outbursts, to the χ^2 one obtains from standard methods when fitting a $\dot{\nu}$ model. So, accounting for a dependence of phase on flux by a simple uniform linear relation produces a significantly better fit than a $\dot{\nu}$ model for 3 of our 9 outbursts. In Fig. 1c we show light curve and inverted phase residuals of J1807 together; clearly there is a good correlation on all timescales, but the relation is not linear. Indeed, Fig. 3 suggests that still better results might be obtained allowing for the more complex (curved or broken) phase-flux relations seen there, but that is beyond scope of this Letter.

In J1808, ν decreases between outbursts; a linear fit to the four mean pulse frequencies gave $\dot{\nu} = -0.56 \pm 0.20 \times 10^{-15}$ Hz/s with $\chi^2/\text{dof}=9.7/2$ (H08). Our new fit has $\dot{\nu} = -1.9 \pm 0.2 \times 10^{-15}$ Hz/s, approximately 3 times that measured by H08. Our $\chi^2/\text{dof}=6.4/2$, reducing to 1.6/2 including the astrometric uncertainty (cf. eq. A1, A2 in H08). While other than H08 we use only the fundamental, whose phase-flux correlation is always detected, the different $\dot{\nu}$ comes from removing the flux bias from the phases.

4. DISCUSSION

Short term (<10 d) correlations or anticorrelations, depending on outburst, between pulse phase and X-ray flux are ubiquitous in our AMXPs, and a considerable fraction, up to $\approx 97\%$ of the variance of the timing noise, can be explained from the X-ray flux variability if we assume that phase depends directly on flux. These correlations can be extended smoothly and maintaining sign to the longest accessible time scales (weeks), i.e., to include a

direct correlation of phase with flux as it decays in each outburst, by a proper choice of pulse reference frequency. This strongly suggests that there is a direct physical link between instantaneous flux level and phase that is very different from the correlation between X-ray flux and spin frequency derivative predicted by standard accretion theory (e.g., Bildsten et al. 1997), and that the pulse frequency derivatives measured in AMXPs are (mostly) not the direct result of accretion torques. Of course, the phase-flux correlation we observe might still (and in fact is plausible to) arise through a common parameter, i.e., accretion rate \dot{M} .

The fact that the observed range of phase residuals is less, and usually much less, than one cycle over each outburst allows an interpretation where a given flux level induces a given constant phase offset by affecting the location of the hot spot on the neutron star surface. Hot spot motion was recently discussed for AMXPs in various contexts. It was observed in numerical simulations (Romanova et al. 2003; Romanova et al. 2004), and it was noted that for hot spots near the rotation pole small linear shifts can cause large pulse phase shifts (Lamb et al. 2008). If the accretion disk inner radius is related with the X-ray flux, then at different flux levels the accreting gas will attach to different magnetic field lines and hence fall on different locations on the surface, producing a hot spot that moves in correlation with flux (and might also change in shape and size, cf. H08, Lamb et al. 2008). The hot spot motion will bias the average frequency over the outburst if the hot spot longitude gradually varies from a different value at the beginning of the outburst to the end, and can mimic the effect of a spin frequency derivative if the light curve is concave or convex. Details in the accretion geometry might make the sign of the correlation positive or negative for near-polar hot spots, but this remains to be calculated. The observed X-ray flux threshold below which the pulse phase deviates from the linear correlation (as in J1814, J0929, J1808, and J1807) might indicate the onset of a different mode of accretion (such as a propeller).

True underlying spin up or spin down episodes during an outburst cannot be excluded from these observations. However, our analyses indicate that if phase depends on flux as we suggest any true *spin* frequency derivative $\dot{\nu}_s$ must be much lower than previously claimed, as the measured $\dot{\nu}$ values primarily result from the X-ray lightcurve concavity. We then interpret the best fit reference frequencies derived under the hypothesis of a uniform phase-flux correlation (Table 1) as our best estimates of the true spin frequency in each outburst. With our new set of spin frequencies for J1808 we infer a long term spindown which, interpreted as due to the magnetic dipole torque, implies a dipole moment of $\mu = 1.4 \pm 0.1 \times 10^{26}$ G cm³ (see Spitkovsky 2006 for a derivation of the non-vacuum magnetic dipole torque) and a magnetic field strength at the poles in the range $B = 2.0\text{--}2.8 \pm 0.2 \times 10^8$ G. This value is slightly smaller than the previous estimate of H08 and agrees with that inferred from optical and quiescent X-ray observations ($B \approx 2 - 10 \times 10^8$ G, Burderi et al. 2003, Di Salvo & Burderi 2003) and with the value expected from standard accretion theory (Wijnands & van der Klis 1998, Psaltis & Chakrabarty 1999).

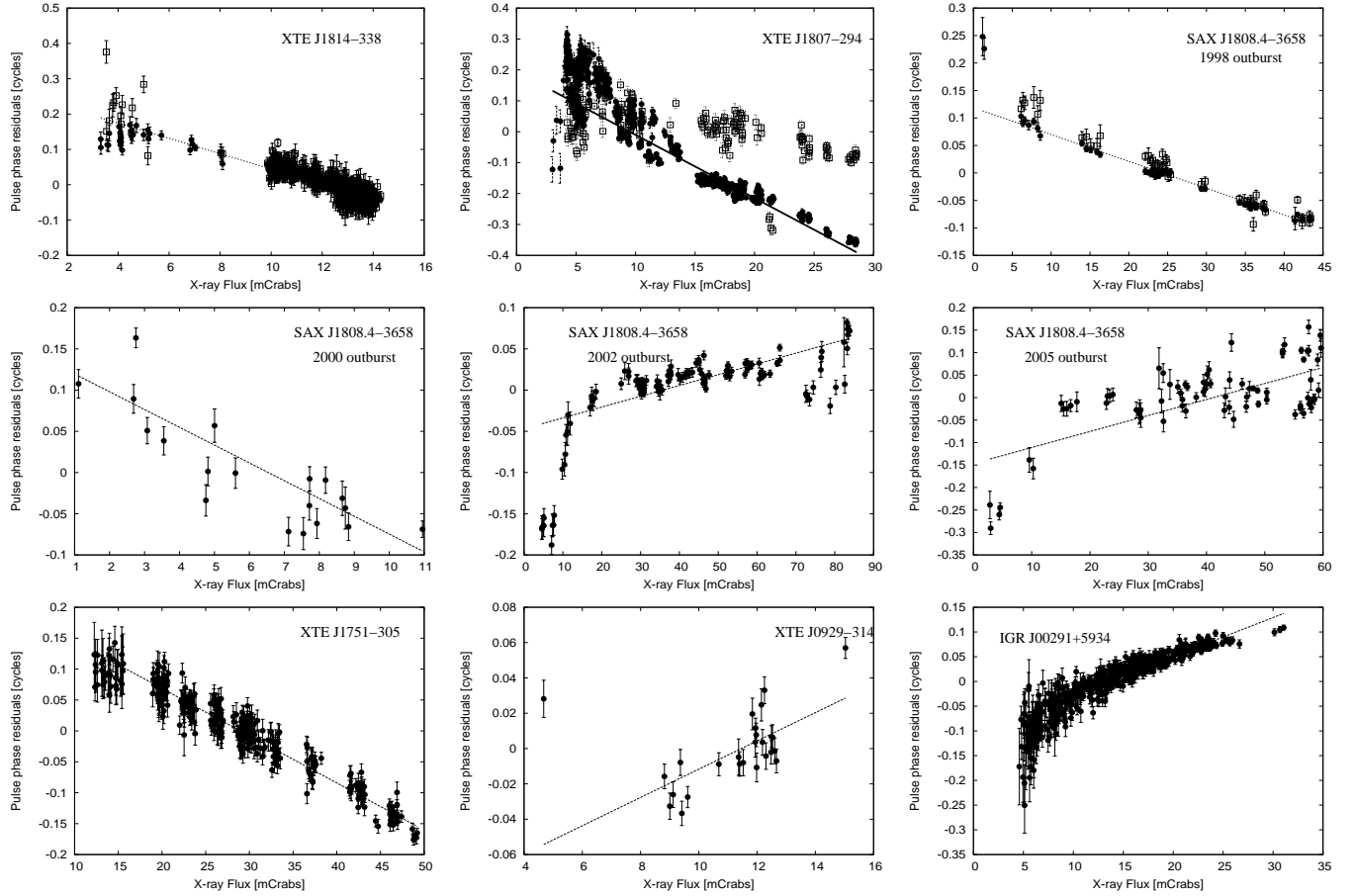


FIG. 3.— Phase-flux correlations for fundamental (*black circles*) and overtone (*gray squares*). Best linear fits to the fundamental phases are shown; deviations mostly occur at low flux. All phase residuals are TOA residual multiplied by pulse frequency, so overtone and fundamental scales match.

TABLE 1
INFERRED SPIN FREQUENCIES

Source name	Short	Outburst date [yr]	ν (Fund., Hz)	ν (1st overt., Hz)	χ^2/dof
XTE J1807-294	J1807	2003	190.62350712(3)	190.62350712(3)	12806.1/765 (F), 1724.5/146 (1st)
XTE J1814-338	J1814	2003	314.35610872(3)	314.35610874(3)	1348/602 (F), 1086.6/555 (1st)
SAX J1808.4-3658 ^a	J1808	1998,2000,2002,2005	0.52(3),0.31(3),0.21(2),0.06(2)	0.50(5)	114/47 (F), 93.6/45 (1st)
XTE J0929-314	J0929	2002	185.10525437(2)		422.1/206
XTE J1751-305	J1751	2002	435.31799405(5)		441.6/306
IGR J00291+5934	J00291	2004	598.89213048(3)		1251.9/521

NOTE. — All the uncertainties quoted correspond to $\Delta\chi^2 = 1$. F=fundamental frequency; 1st=1st overtone

^a The frequencies of J1808 are relative to an offset frequency of 400.975210 Hz. The 1st overtone can be measured only for the 1998 outburst. The χ^2/dof refers to the 1998 outburst.

An open question is why in J1808 in 1998 and in J1807 the correlation is different for overtone and fundamental. A difference in behavior between fundamental and overtone was first noted by Burderi et al. (2006) for the 2002 outburst of J1808, who suggested that due to competing contributions from two poles to the pulse profile the overtone more closely tracks the spin. However, if, as our results suggest, the timing noise in the fundamental can be explained from the flux variations through a moving hot spot model, then after correcting for this the fun-

damental must reflect the spin. We note that, *e.g.*, an \dot{M} dependent competition between fan and pencil beam contributions to the pulse profile would instead primarily affect the phase of the overtone.

In conclusion, our analysis of a large record of AMXP data suggests that \dot{M} induced hot spot motion dominates the observed pulse phase residual variations and that this effect needs to be taken into account when measuring the spin of these neutron stars.

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